

# Numerical study of water barriers produced by underwater explosions

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## Abstract

The U.S. Naval Surface Warfare Center Dahlgren Division (NSWCDD) is developing the technology for a concept that has the potential to be very effective in defending Navy platforms against high speed, sea-skimming Anti-Ship Cruise Missiles (ASCMs). This concept uses a new kill mechanism, which is a wall of water to provide a low cost terminal defense system for Navy ships. This wall of water, or water barrier, is formed from the shallow detonation of multiple underwater explosive charges. To support the development and evaluation of the Water Barrier Concept, underwater detonation tests of scaled line charges were conducted by NSWCDD in July 1995 to determine the amount of water ejected into the air by subsurface detonation of continuous and discrete line charges. Above-the-surface plumes were generated by an underwater detonation of composite C-4 demolition blocks configured into continuous line charges, which were 30 to 56 feet in length. Sequential underwater detonation of discrete line charges consisted of five to eight 10-pound charges each separated by 8 feet and fabricated from C-4 demolition blocks. This paper presents the validation of the mathematic model and computational code for predicting shallow depth explosion plume behavior and compares it with NSWCDD underwater detonation tests. The model is based on a generalized formulation of hydrodynamics and uses an 'incompressible liquid' assumption. The quantitative measurements of plume heights, diameters and plume profiles are compared with the computational data using two-dimensional and three-dimensional discrete line charge models. The plume profiles are studied in detail.

*Keywords: underwater explosion, water barrier, plume, line charge.*



## 1 Introduction

As technology develops, types of warfare become more and more complex and change rapidly. The development of current technology has tremendously changed the military service, and every new military technology is invented according to many factors. Anti-ship missiles are currently the sharpest weapon for the navy and air force to attack ships and buildings on the water surface. To prevent severe damages from anti-ship missiles, the weapons and equipment on ships have to be updated, and the obstructive measures must be improved. Therefore, new techniques for resisting the attack of anti-ship missiles are necessary. Given the magnitude and seriousness of the threat, no option can prudently be ignored.

The Naval Surface Warfare Center, Dahlgren Division (NSWCDD) is developing technology for a concept that has the potential to be effective in defending Navy platforms against high-speed, sea-skimming anti-ship cruise missiles (ASCMs) (Fig. 1) [1]. This concept uses a new kill mechanism, a wall of water (Fig. 2), to provide a low-cost, universal terminal defense system for navy ships. This wall of water or water barrier is formed from the shallow detonation of multiple underwater explosive charges. To support the development and evaluation of the water barrier concept, underwater detonation tests of scaled line charges were conducted in July 1995 to determine the amount of water ejected into the air by the subsurface detonation of continuous and discrete line charges. This concept can be employed to slow or stop target debris and warhead fragments from missiles killed at very short range to preclude significant damage to the ship. Furthermore, the water barrier would defeat the fusing and structure of ASCMs sea skimmers that have penetrated the self-defense layer. Close-in employment of the water barrier concept would increase the engagement space of self-defense weapons and help reduce detection range requirements.



Figure 1: Water plume of an underwater explosion for ship self-defense [1].

This paper studies the characteristics of a water barrier in underwater explosions. A non-linear finite element software MSC.Dytran was used to simulate the water barrier of an underwater explosion. Due to the protection ability being influenced by the shape, width and height of the water barrier, reliable data may be obtained by using two dimensional and three dimensional

models for underwater explosions in a simulated scenario with finite element analysis software; low-cost numerical analysis with high reliability can be utilized for analyzing plume height and density in underwater line charges explosion. The data obtained from the simulation are relatively similar to an actual situation – the advantage is a drastic reduction in costs.



Figure 2: Water plume of an underwater explosion.

In order to study the effect of explosion, the semi-empirical method presented by Cole [2] and Michael and Swisdak [3] is used to study the estimation of underwater and surface effects of an underwater explosion by a single charge. Our result was compared to the report of an underwater explosion with thirteen line charges, conducted by the Naval Surface Warfare Center, Dahlgren Division (NSWCDD). The data retrieved from the camera was compared to the data computed in a numerical simulation. The best combination of elements (depth of line charges, horizontal distance of charge, etc) was investigated, to measure the volume of water splashed into the air, and its possible ramifications.

## 2 Theoretical background

In this paper, the finite element program MSC.Dytran [4] was used for predicting water plume behavior on the air-water surface. MSC.Dytran is a three-dimensional analysis code for analyzing the dynamic, nonlinear behavior of fluid, solid components, and structures. It uses explicit time integration and incorporates features that simulate a wide range of material and geometric nonlinearity. It is particularly suitable for analyzing certain types of occurrences:

- Short, transient dynamic events.
- Those involving large deformations.
- Those involving a high degree of nonlinearity.
- Interactions between fluids and structures.
- Typical applications include: explosive, blasting loading, and underwater shock analysis

Three-dimensional Eulerian elements can be used to create Eulerian meshes. They can handle hydrodynamic materials. A general material facility can be used

to define a wide range of material models, including explosive burn models. Loads can be applied to material in the Eulerian mesh, by pressure or flow boundaries. The initial conditions of element variables can be prescribed. Rigid walls can be created, which act as barriers, obstructing the flow of Eulerian material.

### 3 Numerical study

In this chapter, two-dimensional and three-dimensional models of a discrete line charge were used to conduct the numerical analysis of the shot6 and shot7 sets, as compared to the 13 experiment conducted by Joseph *et al.* [5]. The size of the water surface and the contour generated waves from an underwater explosion were measured, with certain changes in the placement of charges.

#### 3.1 Discrete line charge for constant depth using a two-dimensional model and a three-dimensional numerical model

The results obtained from the numerical analysis by MSC.Dytran were compared and validated with the example of an underwater explosion of discrete line charges carried out by Joseph in 1996.

##### 3.1.1 Problem description

The example of underwater explosion of discrete line charges carried out by Joseph in NSWCCD in 1996 was the object of validation. The discrete line charges are illustrated in Fig. 3. The discrete line charges consisted of 8 10-pound C4 charges. The separation between charges is 8ft, and the total length of the discrete line charge is 56ft. It is located 8.2ft below the water surface to explode.

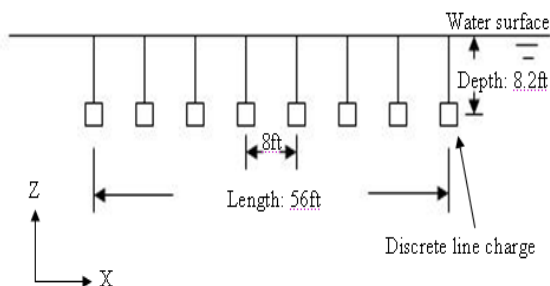


Figure 3: Discrete line charge arrangement at constant depth.

##### 3.1.2 Model description

###### (1) Two-dimensional numerical model

The relative position of the explosives, water, air and water-air surface is shown in Fig. 4. The line charge was parallel to the X-axis, and the symmetric plane

crossed every center of the charges parallel to the X-axis, vertical to the Y-axis. Pressure at the outer boundaries was set to the hydrostatic pressure. The Euler mesh contains water, air-water surface and air. Fig. 5 shows the two-dimensional finite element model used for this problem and consists of 50000 (100m×100m) Eulerian elements and 100902 nodes that contain explosive, water and air. The length of the Eulerian solid element in the x-direction was meshed by 0.4m, and the length in the z-direction was meshed by 0.5m.

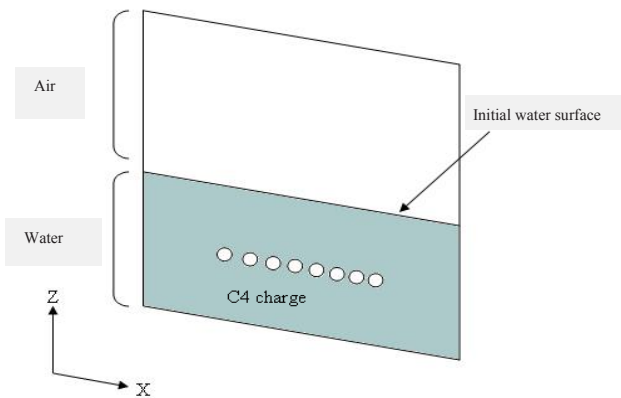


Figure 4: Two-dimensional geometrical model of discrete line charge.

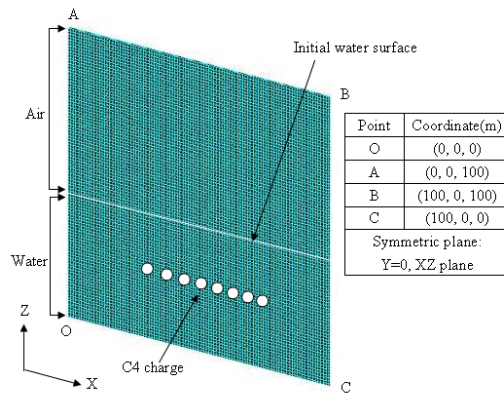


Figure 5: Two-dimensional finite element model of discrete line charge.

A spherical detonation wave front traveling outward from the initiation point at the center of the charge at a velocity of 8193 m/s was used. The explosive C4 was created in this Euler mesh. The density of the explosive is  $1601 \text{ kg/m}^3$  and the mass of every charge is (10 lb) 4.53 kg. The specific internal energy is  $6.657\text{E}6 \text{ kg}\cdot\text{m}^2/\text{s}^2$ . The explosive was modeled by a JWL equation stated in MSC.Dytran. We assumed the explosive to be a ball, the radius of the ball is 0.088 m.

The composition of the seawater used a polynomial equation of state. This state equation accounts for changes in the pressure of the seawater due to density change and specific internal changes. The density of water was  $1025 \text{ kg/m}^3$ . The density of air was  $1.0 \text{ kg/m}^3$ . The ratio of heat capacities of the gas was constant at 1.4. Specific internal energy was taken as  $2.5\text{E}5 \text{ kg}\cdot\text{m}^2/\text{s}^2$ . Initial air pressure is set to  $1.0\text{E}5 \text{ Pa}$ . Gravity load is applied to the whole model.

(2) Three-dimensional numerical model

The relative position of the explosives, water, air and water-air surface is shown in Fig. 6. The three-dimensional model was the model that reflects the whole

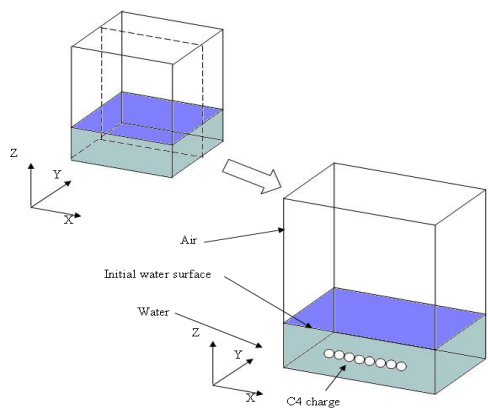


Figure 6: Three-dimensional geometry of discrete line charge.

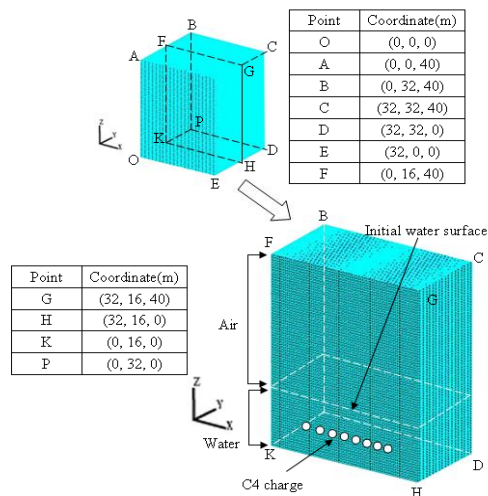


Figure 7: Three-dimensional finite element model of discrete line charge.

scene. Pressure at the outer boundaries is set to the hydrostatic pressure. The Euler mesh contains water, air-water surface and air. Fig. 7 shows the three-dimensional finite element model used for this problem. It consists of 512000 ( $32\text{m} \times 32\text{m} \times 40\text{m}$ ) Eulerian elements and 531441 nodes that contain explosive, water and air. The length of the Eulerian solid element in the x and y directions was meshed by 0.4m, and the length of the z-direction was meshed by 0.5m. The parameter was the same as the ones used in the two-dimensional model.

### 3.1.3 Results and discussion

As shown in Tables 1–3, the range of calculations extended from the water surface to the maximum height that the water barrier could reach. The measurement of the height and thickness of the barrier was based on results obtained by Joseph, at an observation point 11.5ft above the water surface. A comparison of the two-dimensional and three-dimensional models (height, length, thickness) of discrete line charge, to the results of data obtained by Joseph are shown in Figs. 8–10. As shown in these figures, at  $t = 0.1 \sim 0.3$  s after the explosion, the top of the water barrier was still a dense structure. When

Table 1: Surface effect of underwater explosion of discrete line charge.

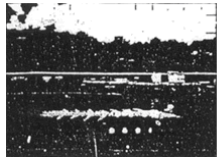
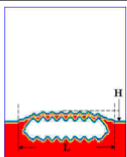
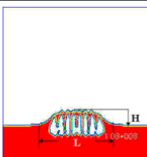
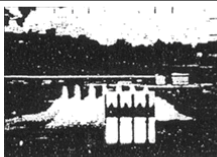
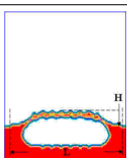
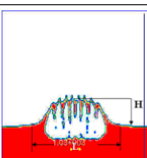
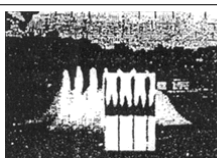
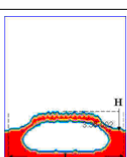
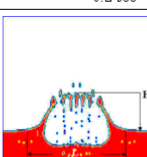
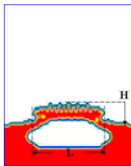
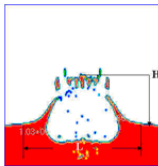
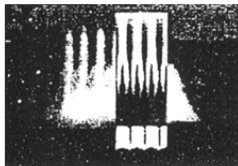
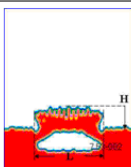
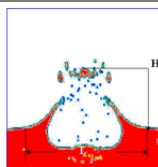
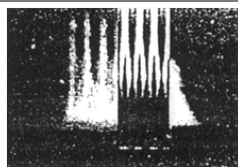
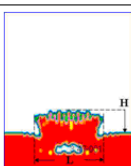
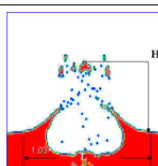
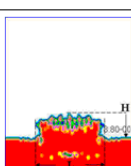
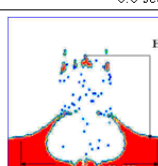
| Present paper                                                                       |                                                                                     | Joseph experiment [ 5 ]                                                             |
|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| 3D model                                                                            | 2D model                                                                            |                                                                                     |
|    |    |    |
| 0.0 sec                                                                             |                                                                                     |                                                                                     |
|   |   |   |
| 0.1 sec                                                                             |                                                                                     |                                                                                     |
|  |  |  |
| 0.2 sec                                                                             |                                                                                     |                                                                                     |
|  |  |  |
| 0.3 sec                                                                             |                                                                                     |                                                                                     |
| H: The height of range of water barrier    L: The length of range of water barrier  |                                                                                     |                                                                                     |

Table 2: Surface effect of underwater explosion of discrete line charge (continuous).

| Present paper                                                                      |                                                                                    | Joseph experiment [ 5 ]                                                           |
|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| 3D model                                                                           | 2D model                                                                           |                                                                                   |
|   |   |  |
| 0.4 sec                                                                            |                                                                                    |                                                                                   |
|   |   |  |
| 0.5 sec                                                                            |                                                                                    |                                                                                   |
|   |   | None                                                                              |
| 0.6 sec                                                                            |                                                                                    |                                                                                   |
|  |  | None                                                                              |
| 0.7 sec                                                                            |                                                                                    |                                                                                   |

H: The height of range of water barrier    L: The length of range of water barrier

$t = 0.4 \sim 0.5$  s, the collapse of the top of water barrier begun. At this time, the size of the water barrier was unstable. We observed that a numerical analysis of the two-dimensional model was clearer and easier to read than that of a three-dimensional model. In Fig. 10, an error at 0.4-0.8 s was noticed. This research used water of 1.0 density. Therefore, both the two-dimensional and three-dimensional models were relatively suitable for analysis in the investigation of discrete line charge.

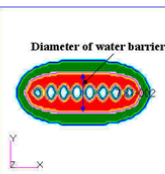
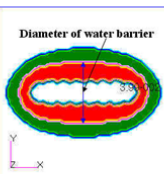
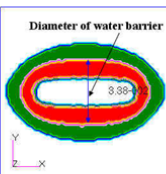
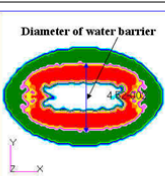
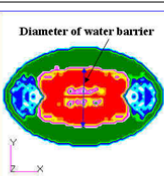
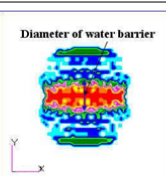
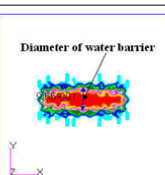
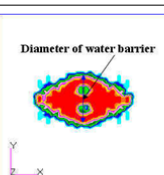
3.2 Comparison of two-dimensional and three-dimensional numerical model for line charge underwater explosion

The discrete line charge consisted of charge blocks of discrete lumped-mass, and it could not be constructed like the surface symmetric model of continuous line charge, which can be constructed by a single charge passing the center.





Table 3: Diameter of water barrier of discrete line charge by three-dimensional model.

| Present paper for 3D model                                                        |                                                                                   |                                                                                   |
|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
|  |  |  |
| 0.1 sec                                                                           | 0.2 sec                                                                           | 0.3 sec                                                                           |
|  |  |  |
| 0.4 sec                                                                           | 0.5 sec                                                                           | 0.6 sec                                                                           |
|  |  |                                                                                   |
| 0.7 sec                                                                           | 0.8 sec                                                                           |                                                                                   |

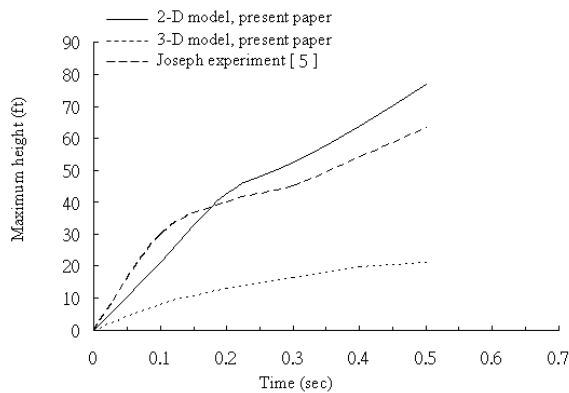


Figure 8: Maximum height of water barrier of discrete line charge for two-dimensional model, three-dimensional model and Joseph experiment.

However, the two-dimensional model of discrete line charge could be constructed with the method of passing every single discrete charge. The result of the measurement of the height of water barrier was good, but a larger error may be caused by the effect of two ends of the line. Proper measurement of the

height of the water barrier may not be stable if the model of the underwater explosion of the discrete line charge was constructed by the three-dimensional model, and the surface effect may vary. The trend remained similar in our measurement of the length of the water barrier having a 20 feet average error. Estimation of the height of the water barrier by a two-dimensional model was relatively good, Estimation of the length of the water barrier by a three-dimensional model was better. By comparing the numerical results of the diameter of the water barrier to the result obtained from the experiment done by Joseph, the value at  $t = 0-0.5s$  was very close, and the diameter was bigger than the one generated from the underwater explosion of continuous line charge. (The diameter of the water barrier generated from the underwater explosion of the continuous line charge was similar to a thin jet, and the diameter was smaller.)

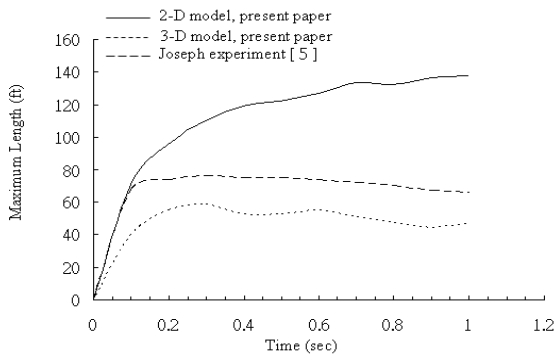


Figure 9: Maximum Length of water barrier of discrete line charge for two-dimensional model, three-dimensional model and Joseph experiment.

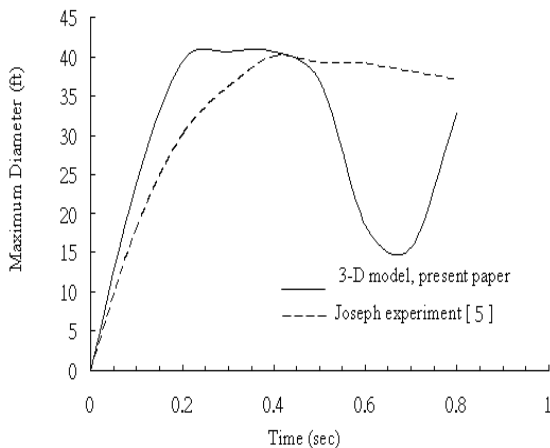


Figure 10: Maximum diameter of water barrier of discrete line charge for three-dimensional model and Joseph experiment.



## 4 Conclusions

A comparison between computational and experimental measurements of height, length, diameter, and thickness of plume produced by an underwater explosion is presented in this study. Of particular interest are the line charge configurations, which created a plume “barrier” by ejecting a “wall of water” above the surface. Such an effect occurs after either of these two situations: the (nearly) simultaneous detonation of discrete charges, placed sufficiently close together in a line, and the detonation of a continuous line of charges. In this study, the FEM software MSC.Dytran was used to create a numerical simulation of the effect of an explosion on the water surface. The results were compared to other experiment data presented by Joseph. Essential conclusions obtained in this project were:

- (1) In the underwater explosion of a discrete line charge, the numerical result obtained from a two-dimensional model was better than that from a three-dimensional model.
  - (a) The two-dimensional model was constructed by fewer elements than the three-dimensional model. The distance between the boundary and the region of explosion was farther and the limitation of the boundary had less effect on the formation of the water barrier.
  - (b) A three-dimensional model was constructed using more elements, though the simulation scene was smaller. The distance between the boundary and the region of explosion was smaller. The compression of air formed a resistant force against the formation of a water barrier. A shock wave would be bounced back from the boundary, affecting the formation of the water barrier.
  - (c) The results of two-dimensional and three-dimensional models showed that the mesh of element is vital. Further tests on boundary conditions are required in order to find better methods of preventing a backflow of water after explosion.
- (2) Two-dimensional and three-dimensional mathematical models can differ from the present MSC.Dytran software application related to such aspects as static hydraulic pressure hypothesis, grid cutting skill, and so formulation of definitions is crucial.
- (3) The proportion of the utilized elements has to be coordinated.
- (4) In this research, some factors are unstable, such as sea currents. The size of the area affected is difficult to control in the open sea. Differences in air pressure may vary under different situations, and must be monitored constantly.

### 4.1 Scope for future research

There are still areas that need to be investigated in the future:

- (1) Optimum depth in underwater explosion of a line charge.
- (2) Optimum distance of charges, in order to generate a better water barrier.



- (3) The effect of charge-configuration on the formation of a water barrier.
- (4) Optimum length of a line charge for the protection of the ship.
- (5) Distance variations between the line charge and the ship.
- (6) Timing of detonation, as related to missile detection.
- (7) Other possible variations in charge deployment.

Underwater explosion tests were conducted to review the development and evaluation of the water barrier ship-defense concept. The barrier plumes were generated from a single-point detonation of C-4 demolition blocks that were configured in continuous and discrete line charges. These line charge configurations demonstrated water barrier plume formation using single-point detonation. This result indicates that water barrier formation and deployment can build on shallow water mine clearance systems that use line charges for a low-cost terminal defense.

It is hoped that the research results in this project can be utilized as reference points in the analysis and design of the protection barrier, designing the structure and equipment in ships, and in the development of anti-vibration devices in underwater buildings.

## Acknowledgement

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